

Adaptive Transceivers in Nonlinear Flexible Networks

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Abstract. *Transceiver adaptation is essential within an optical network to make effective use of the physical layer resources. We investigate the types of adaptation, the granularity of control and its effect on network data throughput.*

Introduction

Within a wavelength routed optical network the allocated light paths will have a variety of propagation lengths, accumulating different impairments and leading to a range of received signal quality. The transmitted signal should be adapted to ensure the limited resources of bandwidth and light path SNR are used effectively. Software defined transceivers can adapt the transmitted signal to the prevailing light path conditions, can apply sophisticated impairment mitigation schemes and adapt their bandwidth to the clients requirements. It is important to understand the advantage of the different adaptation approaches, in a network context, and how these might be used.

To maximise the data transmitted over a given light path the transceivers can use basic modulation format adaptation¹, 4D modulation schemes², time division hybrid formats³, probabilistic shaping^{4;5} and FEC overhead (OH) adaptation^{6;7;8;9}. The adaptation of the optical launch power^{10;11} and mitigation of non linear interference using, for example digital back propagation (DBP)^{12;13}, can improve the properties of the light path. While the use of flexible grids with adaptive signal bandwidth¹⁴, superchannels and sliceable transceivers¹⁵ allows the light path bandwidth to be better matched to the clients data requirements.

One very important consideration for adaptation is the granularity with which the signal parameters can be adjusted, i.e. the quantisation of the adaptable parameters. For example if we consider adaptation between square PM-mQAM formats with fixed FEC OH then the spectral efficiency changes in steps of $4 \text{ b}\cdot\text{s}^{-1}\cdot\text{Hz}^{-1}$ and the required SNR changes in steps of $\approx 6 \text{ dB}$.

Within the transceiver adaptation we have granularity in the client side data rate, modulation format, FEC OH, optical bandwidth and launch power. This paper will begin by investigating the effect of the granularity in the adaptation of the combination of FEC and modulation format, usually known as coded modulation. We consider a

simple link and a mesh network based on the 9 node 17 link German backbone network¹⁶ and as shown in figure 1. We investigate the data throughput as a function of the length of the shortest link, while maintaining the topology, to obtain the understand the typical effect of adaptation and avoid enhanced gains due a fortuitous length scale.

Coded Modulation Adaptation Granularity

In this work we assume ideal data transmission where each light path, with a given SNR, can transport data at the AWGN capacity. Granularity is added by quantising the data throughput to the nearest 25 or 100 $\text{Gb}\cdot\text{s}^{-1}$ below the AWGN capacity.

For the physical network we consider a transparent optical infrastructure composed of nodes formed of ideal ROADMs and links formed of a number of equal length fibre spans with EDFA to compensate for the span loss. We consider polarisation multiplexed coherent optical signals operating on a fixed 50 GHz grid, a total of 80 channels each of 32 GBaud. It is assumed that linear impairments are ideally compensated at the receiver and that the only significant physical layer impairments are ASE noise from the EDFAs and nonlinear interference. The nonlinear interference is estimated

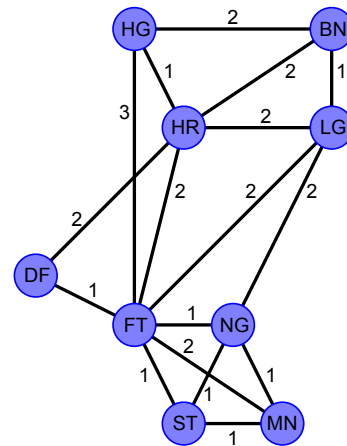


Figure 1. Topology of the 9-node mesh network considered, based on the DT network¹⁶ and showing relative link lengths.

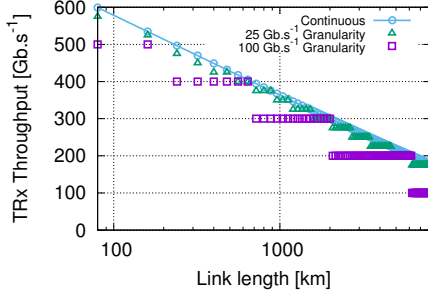


Figure 2. Light path data throughput of a link as a function of its length for continuously adapted AWGN capacity and two levels of granularly adapted AWGN capacity.

using the Gaussian noise model¹⁷ assuming the links are fully loaded and all operating at the same launch power.

For each light path the SNR of the received transmission is estimated as

$$SNR = \frac{p_0}{N_s n_{ASE} + N_s \eta_{XPM} p_0^3 + N_s^{(1+\epsilon)} \eta_{SPM} p_0^3} \quad (1)$$

where N_s is the number of spans in the light path, n_{ASE} is the ASE noise from a single amplifier, η_{XPM} is the nonlinear interference coefficient for the total of all cross phase modulation (XPM), η_{SPM} is the nonlinear interference coefficient for self phase modulation (SPM) and ϵ is the coherent factor for SPM. The traditional four wave mixing (FWM) is assumed to be negligible. p_0 is the launch power on all channels and is optimal for the central channel of the link and is near optimal for the mesh network being optimal for the central channel over the mean shortest path.

For the link the physical layer model was used to estimate the SNR of the light paths. Given this SNR the maximum throughput of each light path was calculated as the quantised AWGN capacity. Figure 2 shows the throughput of a light path on the link as the number of spans and thus length of the link is increased. It can be seen that at some distances the throughput is equal to the AWGN capacity regardless of the quantisation, and that with finer quantisation of the adaptation the worst case deviation from this AWGN capacity is significantly reduced.

For the network case the data throughput is defined as the total of all the data transported that satisfies a uniform all to all traffic matrix as defined in section III of⁹. The maximum throughput of the network was found by optimally solving the routing and wavelength assignment (RWA) using an integer linear program (ILP). The k-shortest light paths between each node pair where pre-calculated, along with their SNR and supported data rate. The ILP allocates transmitters to light paths and wavelengths, to maximise the overall network throughput subject to the uniform traffic matrix being satisfied, wavelength continuity and

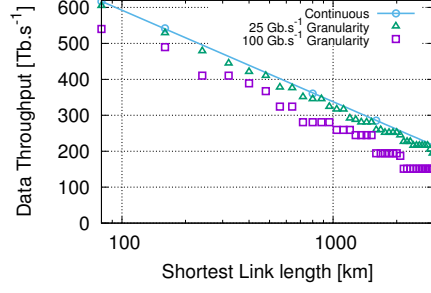


Figure 3. Total uniform all to all data throughput of the mesh network of figure 1 as a function of shortest link length for continuously adapted AWGN capacity and two levels of granularly adapted AWGN capacity.

no wavelength collisions¹¹.

Figure 3 shows the total network throughput as a function of the number of spans in the shortest link. It can be seen that with finer granularity the network throughput converges to the continuous adaptation case. The averaging effect of multiple path lengths within the network solution reduces the probability that the total data throughput is equal to the continuously adapted AWGN capacity, since all light paths would need to have a data throughput equal to their continuously adapted cases.

To compare the link and network case we consider the capacity gap between the quantised and continuous adaptation per transceiver. Table 1 shows the mean capacity lost per transceiver and its standard deviation. It can be seen that the mean capacity lost per transceiver is similar for the link and the network being approximately half the adaptation granularity. However the standard deviation of the lost capacity is lower for the network case due to the averaging effect of the different light path lengths in the network solution. Thus we can expect that in a larger network with more light path lengths the data throughput will converge with a lost capacity of half the adaptation granularity per transceiver. This provides an insight into the how the effect of the adaptation granularity estimated in a link can be applied to a network.

Table 1. Mean lost capacity per transceiver.

Quantisation	Loss per transceiver [Gb.s ⁻¹]	
	100 Gb.s ⁻¹	25 Gb.s ⁻¹
P2P Link	52.0 ±32.4	12.3 ±7.1
DT Network	59.2 ±11.5	14.1 ±4.6

Observations and Discussions

Adapting the transceiver parameters to the properties of the light path in a network allows for more effective use of the network resources. The granularity with which these transceiver parameters can be changed is important to fully utilise the available resources. We have shown that the mean (over different length scales) of the lost capacity is approximately half the adaptation granularity for

Table 2. Advantages and disadvantages of different combinations of transceiver adaptation.

Client Data Rate	Modulation Format	FEC OH	Optical BW	Launch Power	Notes Advantages - Disadvantages
Coarse	Coarse	Fixed	Fixed	Fixed	Basic adaptation - Wasted SNR
Coarse	Coarse	Fixed	Fixed	Variable	Coarse client - Complex RWA, needs DBP
Flexible	Fine combined adaption		Fixed	Fixed	Separate line & transceiver opt. - Flexible client
Coarse	Fine combined adaption		Flexible	Fixed	Coarse client, separate line & transceiver opt. - RWA contiguity constraint, fragmentation

both links and mesh networks. This can give some basic insight into the advantages of a particular adaptation technique within a complex network environment.

It is interesting to consider how the different adaptations might be used and combined. The first use of adaptation was a simple coarse modulation format adaptation with other parameters fixed. While this begins to utilise the higher SNR available for shorter light paths the coarseness of the adaptation means that many light paths will be under used. In¹⁰ we showed it was possible to overcome the mismatch between the light path SNR and the modulation required SNR while keeping the coarse modulation format adaptation by adjusting the launch power albeit with some considerable increase in the complexity of RWA and the use of DBP.

In order to simplify the network management it would be advantageous to separate the line optimisation from the transceiver optimisation. That is separate the optimisation of launch power, EDFA gain, and other components forming the optical line and the optimisation of the transceiver parameters. In this case we must adapt the transceiver coded modulation with fine granularity to effectively use the SNR of the light path. Given a separately optimised line and coded modulation we can either have a fixed optical bandwidth and flexible client side data rate or a flexible optical bandwidth to meet the required client side data rate. The advantages and disadvantages of the various adaptation options are summarised in table 2.

Further investigations into the effects of combined adaptation and the use of DBP will be presented.

Acknowledgements & Data Access

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Additional data related to this publication is available at the University of Cambridge data repository, <https://www.repository.cam.ac.uk/handle/1810/255962>.

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